



Stored Light in an Optical Fiber via Stimulated Brillouin Scattering

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Materials and Methods

Figs. S1 to S3

References

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REPORTS

Stored Light in an Optical Fiber via Stimulated Brillouin Scattering

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We describe a method for storing sequences of optical data pulses by converting them into long-lived acoustic excitations in an optical fiber through the process of stimulated Brillouin scattering. These stored pulses can be retrieved later, after a time interval limited by the lifetime of the acoustic excitation. In the experiment reported here, smooth 2-nanosecond-long pulses are stored for up to 12 nanoseconds with good readout efficiency: 29% at 4-nanosecond storage time and 2% at 12 nanoseconds. This method thus can potentially store data packets that are many bits long. It can be implemented at any wavelength where the fiber is transparent and can be incorporated into existing telecommunication networks because it operates using only commercially available components at room temperature.

An information network consists of nodes where information is generated, processed, routed, and stored, and of transmission links that interconnect the nodes. One bottleneck in modern optical information networks is the lack of an all-optical memory for which the storage time is continuously adjustable (*1*). Substantial progress has been made in the development of a memory based on spatial-spectral holography (*2*), but this method requires operation at cryogenic temperatures. Another promising approach is so-called stored or stopped light based on electromagnetically induced transparency (EIT), in which information encoded on an optical beam is impressed upon internal

degrees of freedom of a dense atomic ensemble (*3–7*). Storage times exceeding 1 s have been observed for a 20- μ s-long pulse (*8*), suggesting that this method could be useful as a component in long-distance quantum information networks (*9, 10*). One limitation of both of these storage methods is that their frequency of operation is highly constrained: The frequency of the stored light must match precisely the resonance frequency of the ions or atoms used. These constraints have been cast aside with the prediction (*11*) that a pulse can be stored in a dynamically controlled microring resonator containing many narrow resonances over a broad spectral range, and a single optical pulse was stored for ~ 100 ps in a proof-of-concept experiment (*12*).

Here, we demonstrate storage of multiple optical pulses by coherently transferring their information content to an acoustic excitation in a room-temperature optical telecommunication fiber through their interaction with an additional

optical “write” pulse. After a controllable storage time, the acoustic excitation is converted back to the optical domain by interaction with a “read” pulse. The process is based on stimulated Brillouin scattering (SBS) (*13, 14*) and works at any wavelength where the fiber is transparent, including the important telecommunication band in the near-infrared spectral region. The SBS process arises from electrostriction, in which a time-varying electric field creates a time-varying change in density of the material system (i.e., an acoustic excitation). The acoustic wave modulates the refractive index of the medium, which induces both amplifying and absorbing resonances in the vicinity of the applied laser frequencies. Our storage scheme relies on the process of anti-Stokes absorption, which occurs efficiently when the carrier frequency (central frequency) of the incident data pulses is higher than the carrier frequency of the applied write pulse by the Brillouin frequency shift Ω_B , which is proportional to the speed of sound in the material and is approximately 9.6 GHz for our fiber at wavelengths near 1.55 μ m. The SBS process works for data pulses at any carrier frequency so long as the write- and read-pulse frequencies are lower than the data-pulse frequency by Ω_B ; this condition can be achieved easily using standard tunable-laser technology.

Our experiment to demonstrate light storage in an optical fiber is conceptually very simple. Bits of information, represented by pulses of light, pass through the fiber while, simultaneously, a write pulse passes through the fiber in the opposite direction (Fig. 1A). Through the process of SBS, essentially all the data-pulse energy is depleted and a coherent acoustic excitation is left behind in the

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Fig. 1. Storage of data pulses as an acoustic disturbance in an optical fiber and their subsequent retrieval after a controllable time interval. In the storage process, a short, intense write pulse that is detuned to the low-frequency side of the data-pulse frequency by the Brillouin frequency shift causes the data pulses to become depleted (A) with the information being stored as an acoustic wave in the medium (B). In the retrieval process (C), a short, intense read pulse at the same frequency as the write pulse depletes the acoustic wave and converts the data back to the original optical frequency, thereby producing a replica of the incident data pulses (D).

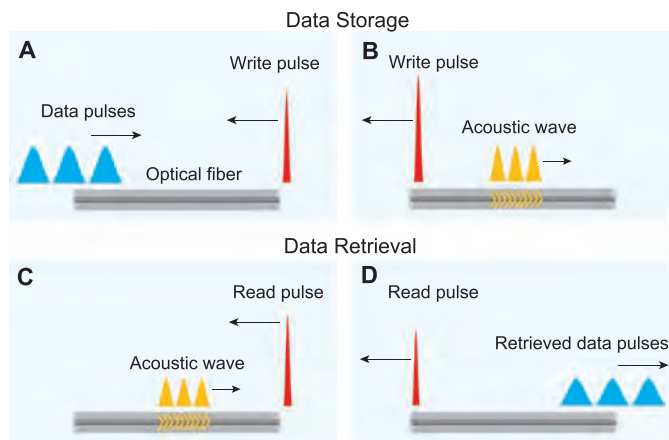


Fig. 2. Observation of stored light. (A) shows experimental results for a 2-ns-long rectangular-shaped data pulse, and (C) shows the corresponding theoretical simulations. (B) shows the case of a 2-ns-long smooth data pulse, with the corresponding simulations shown in (D). The retrieved pulses are shown with a multiplication factor of 2 to the right of the dashed vertical line.

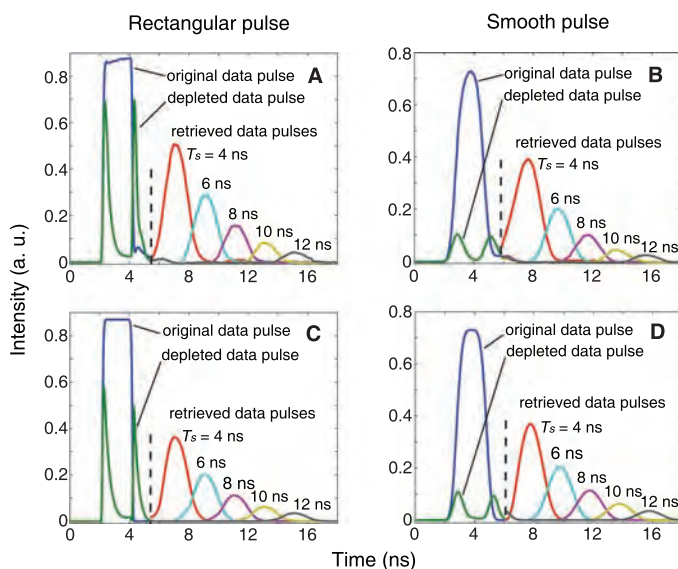
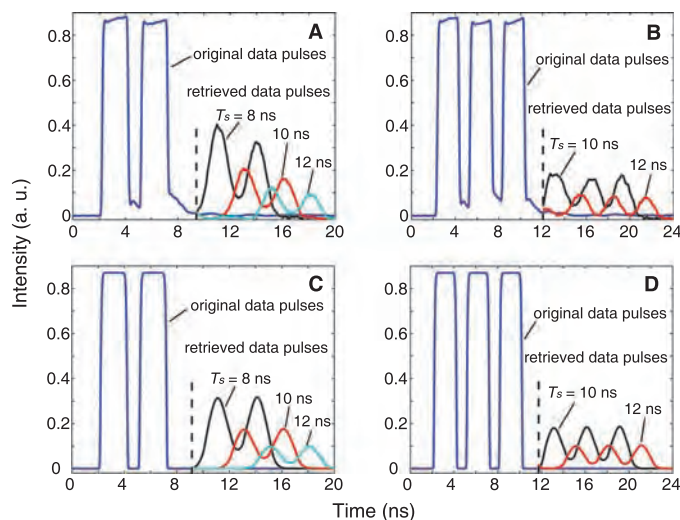


Fig. 3. Storage of pulse sequences. (A) shows experimental results for two 2-ns-long data pulses separated by 1 ns, and (C) shows the corresponding theoretical simulations. (B) shows the case of three 2-ns-long data pulses separated by 1 ns, with the corresponding simulations shown in (D). The retrieved pulses are shown with a multiplication factor of 5 to the right of the dashed vertical line. For clarity, the depleted data pulses are not shown.



fiber, which contains the information content of the data pulses (Fig. 1B). Only a small fraction of the data-pulse energy is converted to the acoustic excitation; most of it is transferred to the write pulse. At a later time, a read pulse passes through the fiber in the same direction as the write pulse (Fig. 1C). It depletes the acoustic excitation, and the data pulses are released from the fiber, propagating in the same direction as the original data pulses (Fig. 1D). Energy from the read pulse is transferred to the released data pulses in this process.

Our approach has some relation to previous pulse-storage methods. It can be thought of as a form of real-time holography, and it is related to the process of the stimulated photon echo familiar in magnetic resonance imaging (but operating at much higher efficiency). Also, it has been predicted (15, 16) that light pulses can be stored via Raman backscattering induced in a plasma, although this effect has not been observed experimentally.

As with EIT-based stored-light methods, nearly 100% storage and retrieval efficiency can be obtained in our approach when various conditions are satisfied. In analogy to work with driven two-state systems (such as in nuclear magnetic resonance), we define a pulse area as $\Theta = \sqrt{g_B v_g n_f \epsilon_0 c / 16 \tau_B} [A_c(t) dt]$, where the integration is carried over the duration of the pulse, g_B is the SBS intensity gain coefficient, v_g is the group velocity of the pulses in the fiber, n_f is the modal refractive index of the fiber, ϵ_0 is the vacuum permittivity, c is the light speed in vacuum, τ_B is the acoustic lifetime, and A_c is the electric-field envelope of the write or read pulse (17). Complete storage of the data waveform is possible when four conditions are met. The first is that $\Theta = \pi/2$ for both the write and read pulses. The second condition is that the write and read pulses must have a duration that is shorter than the shortest-duration data pulse to be stored. Under this condition, the entire spectrum of the data pulses can be faithfully recorded and retrieved. Third, the storage time T_s must be less than the acoustic lifetime τ_B . Last, the spatial extent of the data packet must be less than twice the length of the storage material.

These ideal conditions can be satisfied only approximately in typical experiments, where compromises must be made because of material and equipment limitations. For example, for constant pulse area, the peak power of the write or read pulses scales inversely with the square of the pulse duration. Hence, the shortness of the write and read pulses is limited only by the available pulse power. Also, the readout efficiency decreases rapidly when the storage time exceeds the acoustic lifetime τ_B , which places a bound on the total length of the data packet. For a packet storage time of T_s , the maximum retrieval efficiency is $\exp(-T_s/\tau_B)$. The time constant τ_B depends on

material parameters, such as the viscosity, and scales quadratically with the wavelength of the optical pulses. It equals ~ 3.4 ns for our storage material, so that our current system is most appropriate for high-data-rate communication systems.

We use a short length of commercially available optical fiber and light pulses with a center wavelength around $1.55\ \mu\text{m}$, which is in the middle of the telecommunication band (17). Fig. 2A shows the experimental results for storing and retrieving a single rectangular-shaped 2-ns-long data pulse using identical, 1.5-ns-long write and read pulses with peak powers of ~ 100 W. To the left of the dashed vertical line, the incident data pulse in the absence and presence of the write and read pulses is shown by the blue and green lines, respectively. The energy storage efficiency of the storage process is very high—equal to $\sim 66\%$ —indicating that we have faithfully encoded the optical pulse information onto the acoustic material excitation.

The data pulses are released from the fiber after a controllable storage time T_s by applying a read pulse, which converts the acoustic material excitation back to the optical domain. The curves to the right of the vertical dashed line are the observed retrieved pulses, where we have scaled them by a factor of 2 for clarity. For $T_s = 4$ ns, we obtain a readout energy efficiency of 25%, defined as the energy of the released pulse divided by the energy of the incident data pulse. For $T_s = 12$ ns, the storage time is equal to 6 pulse widths with an efficiency of 1.8%. These observations suggest that this method is useful for a class of high-speed, all-optical information processing applications, such as pulse correlation (18). Consistent with the discussion above, we see that the readout efficiency drops with increasing storage time as a result of the decay of the acoustic wave.

The fast rising and falling edges of the data pulse in the time domain contribute to its high-frequency content in the frequency domain. Thus, we hypothesize that the edges are not fully stored because the write-pulse spectrum is not broad enough to fully encompass the data-pulse spectrum; its spectrum is only slightly wider than the data-pulse spectrum. To test this hypothesis, we stored and retrieved a smoothed data pulse, as shown in Fig. 2B. In this case, the energy storage efficiency increases to 86% and the readout efficiencies are improved slightly ($\sim 29\%$ for $T_s = 4$ ns).

To verify the interpretation of our results, we have solved numerically the equations governing the interaction between the optical and acoustic waves in an optical fiber. The simulations (Fig. 2, C and D) are in good agreement with observations (17).

Fig. 3, A and B, shows our observations for the storage and retrieval of sequences of two and three data pulses, respectively. For clarity, we show only the input data pulses to

the left of the dashed vertical line and to the right we show the retrieved pulses scaled by a factor of 5. The light released from the fiber clearly replicates the input data stream with reasonable fidelity. Again, the numerical simulations (Fig. 3, C and D) are in good agreement with the observations (Fig. 3, A and B).

Our results demonstrate that coherent optical storage can be realized without the use of atomic spin coherence such as that used in EIT-based stored light. Longer storage times may be expected using materials with longer acoustic lifetimes, such as chalcogenide glass fibers ($\tau_B = 12$ ns for As_2Se_3 at a wavelength of $1.55\ \mu\text{m}$) (19) or high-pressure gases ($\tau_B = 80$ ns for Xe at 140 atm and a wavelength of $1.55\ \mu\text{m}$) (13). Also, the peak powers of the write and read pulses can be lowered substantially using fibers with a larger SBS gain coefficient (e.g., g_B for As_2Se_3 is 134 times as large as that of silica) (19) or smaller core sizes (i.e., smaller mode area). With such improvements, our method should be suitable for use in the buffering of information and for all-optical data processing such as correlation and convolution.

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Figs. S1 and S2
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Mott Transition in VO_2 Revealed by Infrared Spectroscopy and Nano-Imaging

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Electrons in correlated insulators are prevented from conducting by Coulomb repulsion between them. When an insulator-to-metal transition is induced in a correlated insulator by doping or heating, the resulting conducting state can be radically different from that characterized by free electrons in conventional metals. We report on the electronic properties of a prototypical correlated insulator vanadium dioxide in which the metallic state can be induced by increasing temperature. Scanning near-field infrared microscopy allows us to directly image nanoscale metallic puddles that appear at the onset of the insulator-to-metal transition. In combination with far-field infrared spectroscopy, the data reveal the Mott transition with divergent quasi-particle mass in the metallic puddles. The experimental approach used sets the stage for investigations of charge dynamics on the nanoscale in other inhomogeneous correlated electron systems.

One challenge of contemporary condensed matter physics is the understanding of the emergence of metallic transport in correlated insulators or Mott insulators in which, for example, a temperature change or chemical doping induces anomalous conducting phases (1). In such a correlated metal, the mobile charges experience strong competing interactions leading

to exotic phases, including the pseudogap state in cuprates and manganites, high-temperature superconductivity, charge stripes in cuprates, and even phase separation in some manganites and cuprates (1–8). In systems where multiple phases coexist on the nanometer scale, the dynamical properties of these individual electronic phases remain unexplored because methods appropriate to study charge